CRYO-COOLED SAPPHIRE OSCILLATOR WITH ULTRA-HIGH STABILITY

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ABSTRACT

We present design details and test results for the first short-term frequency standard to achieve ultra-high stability ($\sigma_y < 10^{-14}$) without the use of liquid helium. Technical features include vibration isolation by atmospheric helium gas and a new sapphire resonator design with adjustable compensation operating at 8-10K.

SUMMARY

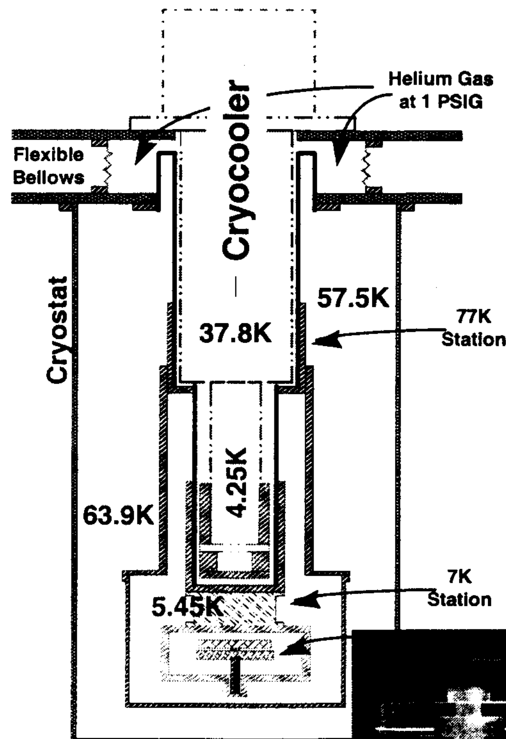
Cryogenic oscillators operating below about 10K offer the highest possible short term stability of any frequency sources. However, their use has so far been restricted to research environments due to the limited operating periods associated with liquid-helium cooling.

We are developing a cryogenic sapphire oscillator for ultra-high short term stability and low phase noise in support of the Cassini Ka-band Radio Science experiment. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} (1 second $\leq \tau \leq$ 100 seconds) and a phase noise of -73dB/Hz @ 1Hz measured at 34 GHz. Installation of these oscillators in stations of NASA's deep space network (DSN) is planned in the years '00 - '02.

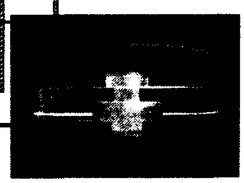
Continuous long-term operation is crucial to the applicability of short-term frequency standards since they are typically are used to "clean up" the short-term variations of a longer term atomic standard, the combined output being then distributed to various users. Furthermore, the cryogenic oscillators provide local oscillator (L.O.) performance as required by a new generation of passive atomic standards. These include the Cesium Fountain and Trapped Ion standards which are under development at many laboratories around the world, and whose potential presently cannot be met using other technologies. Because these *are* long-term frequency standards, continuous operation of the L.O. is crucial to its applicability.

Our development was enabled by a new generation of 2-stage Giffard-McMahon (GM) cryocoolers which allow operation at temperatures down to 4.2K. Previously, such temperatures could only be achieved by the use of an additional Joule-Thompson expansion stage, with increased complication and cost, and with reduced reliability due to the likelihood of clogging the small expansion leak.

Any cryocooler generates vibrations which, if coupled to a high-Q electromagnetic resonator, would degrade its frequency stability. However, the requirements associated with Mössbauer experiments are as stringent as ours, and the experimental Mössbauer community has successfully adopted a methodology that transfers heat from the experiment to cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas.



Cryogenic and Vibration Isolation Systems Showing Measured Temperatures



Ruby and Sapphire Resonator Elements

A small Dewar fits closely around the cryocooler with the space between them filled with helium gas at atmospheric pressure. This methodology, which has not previously been applied to frequency standards, allows the cryocooler and cryostat to be independently supported.

Sapphire resonators have been tested which show quality factors of $Q \approx 10^9$ at temperatures up to 10K. However, stable operation can only be achieved near a preferred "turnover temperature" which is typically too low (1.5K-6K) to reach with by cryocooler, and which varies from resonator to resonator depending on the concentration of incidental (~1 PPM) paramagnetic impurities.

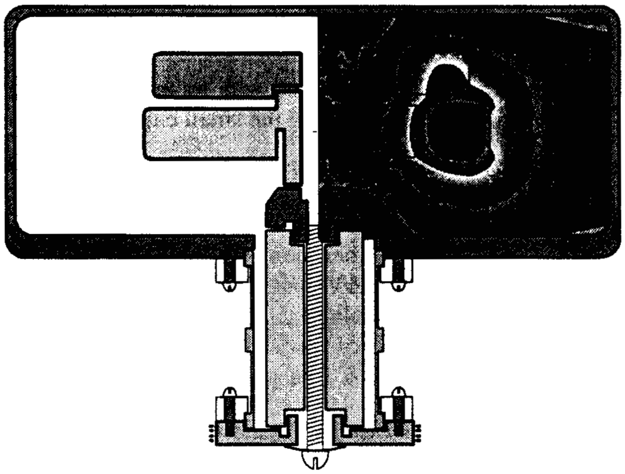


Figure 2 Externally compensated sapphire resonator assembly with calculated rf fields.

Because impurity levels cannot be accurately controlled in the resonator, we have developed an externally compensated resonator[1] that uses paramagnetic chromium impurities in a thermally attached ruby element to provide an adjustable compensation in the relatively narrow temperature band between that which can be realistically achieved with available cryocooler cooling (7-8K) and the point at which the Q is degraded (10K).

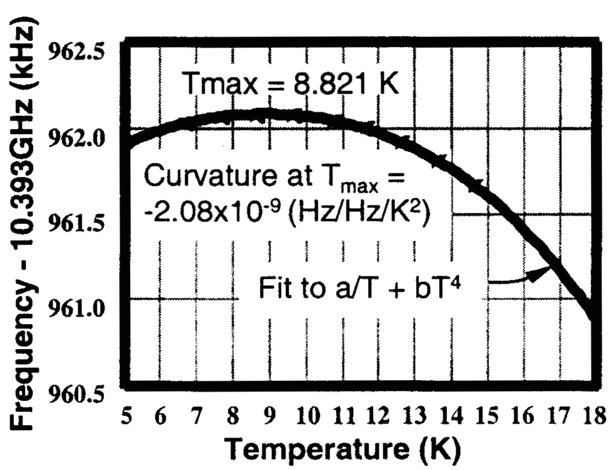


Figure 3 Temperature turnover of externally compensated sapphire resonator.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at much higher temperatures. A resonator with a mechanical compensation scheme has achieved stability of better than 1×10^{-13} at a temperature above 77K, and combined sapphire-rutile resonators are presently under study. However, the Q values of a million or so that are so far achievable with these schemes are far below those desired.

Fig. 3 shows the first reported frequency turnover for a resonator with adjustable compensation and ultra-high Q. The turnover temperature at 8.821K is reasonably close to the value of 7.25K calculated from finite element calculations together with previously measured properties for the ruby element.[1] The Q at 8-10K was about 300 million with or without the ruby compensating element. The mode excited is $WGE_{14,1,1}$ at 10.395 GHz.

Fig 4 shows frequency stability measurements for a frequency standard implemented with this resonator using a Pound frequency locking method with a 2MHz modulation frequency.

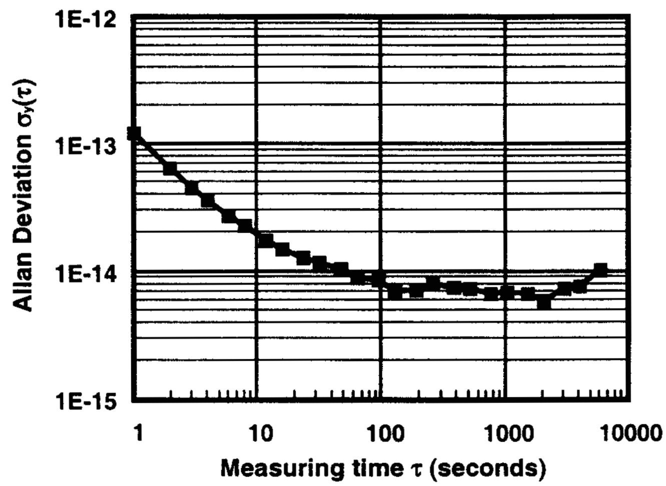


Figure 4 Measured frequency stability with hydrogen-maser reference.

As shown in the figure, a floor of 7×10^{-15} is observed for times longer than about 100 seconds, with short term stability limited by the hydrogen-maser reference. Phase noise measurements also show maser-limited performance.

A second, identical, cryocooled standard is presently under construction. Comparison of the two will allow short term performance to be accurately characterized for the first time.

Reference

1. J. Dick and R. T. Wang, "Cryocooled saphire oscillator for the CASSINI Ka-band Experiment," *Proc. 1997 International IEEE Frequency Control Symposium*, 1009-1014 (1997).